POLARIMETRIC PROPERTIES OF TRANSNEPTUNIAN OBJECTS AND CENTAURS

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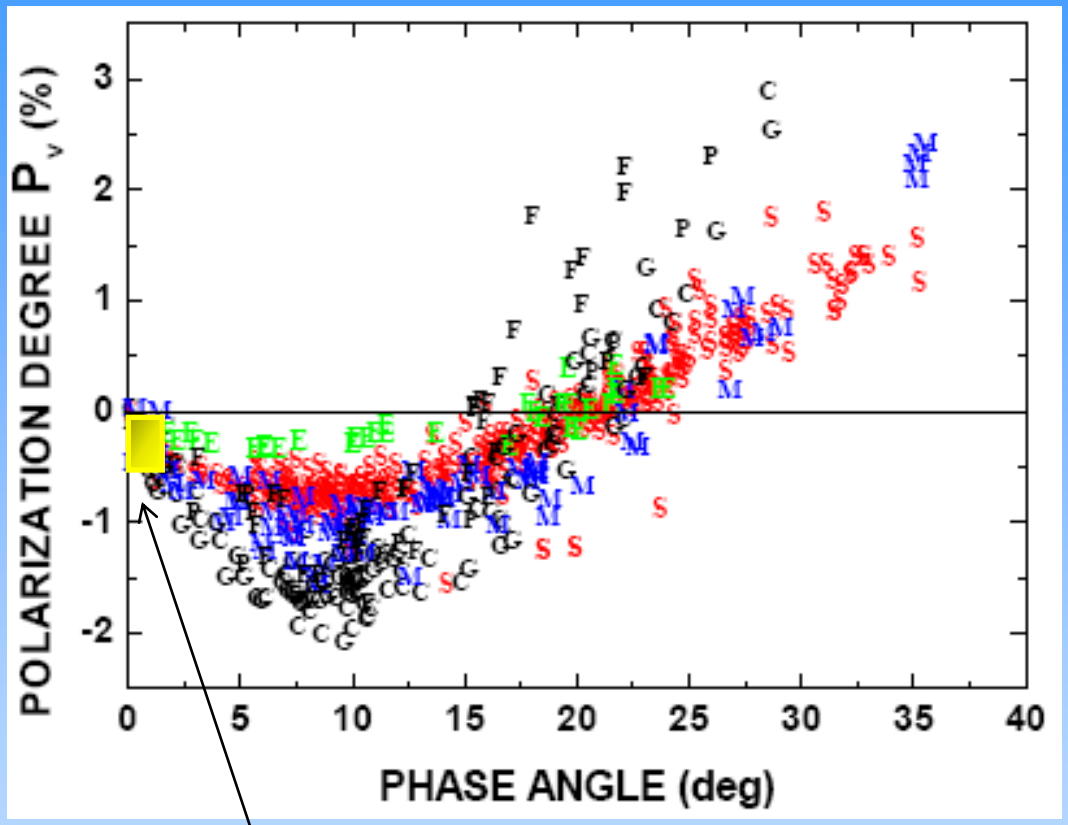
POLARIZATION PHASE ANGLE DEPENDENCE

Main-belt asteroids

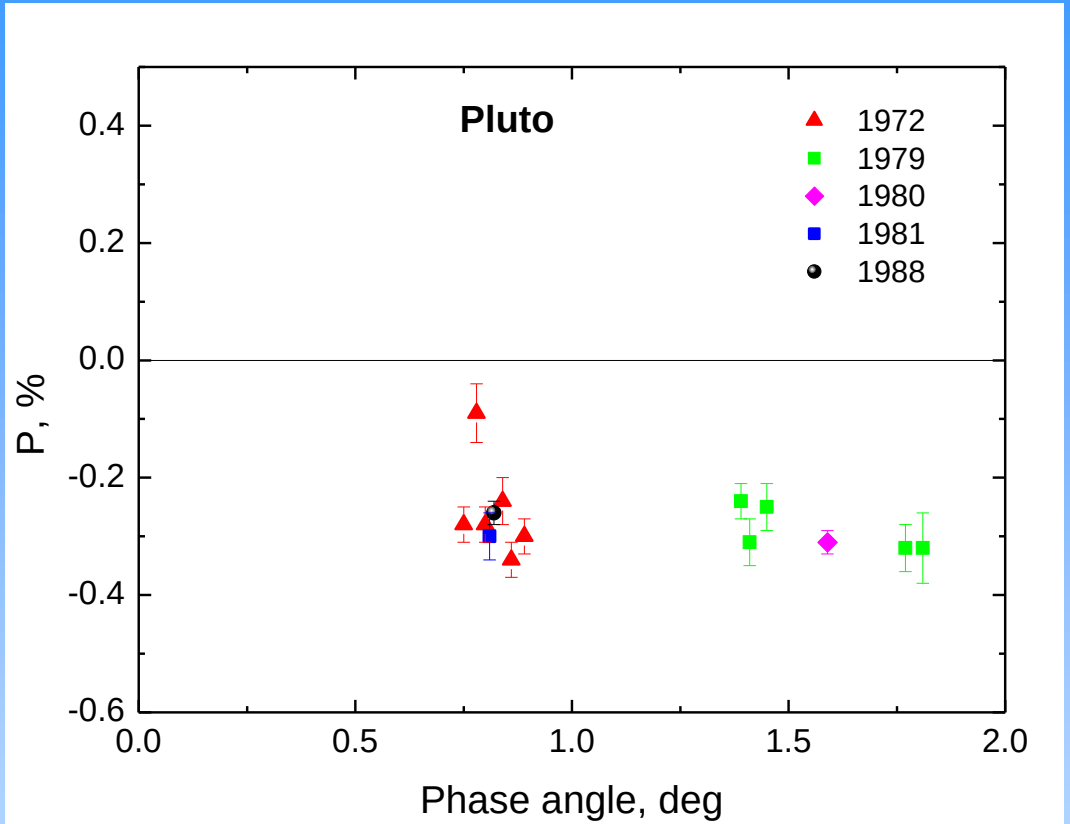


Geometry of the ground-based observations of distant objects is very limited:

r	α
3 AU	**19.5°**
10 AU	**5.8°**
40 AU	**1.4°**

Phase angle range for TNOs

FIRST MEASUREMENTS OF POLARIZATION FOR A TNO



Kelsey & Fix 1973
Breger & Cochran 1982
Avramchuk et al. 1992

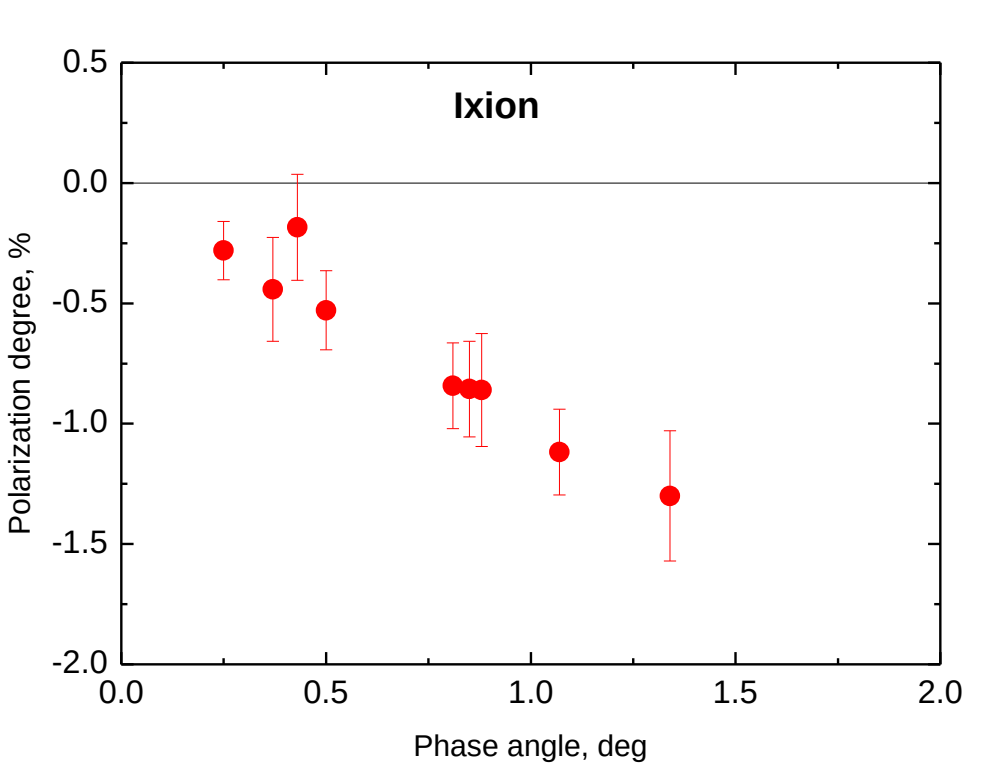
V~ 15 mag
Telescopes: 1 m, 1.3 m, 2 m
σ_P~0.03-0.05%
V (1979-1981) or without filters

- negative polarization
- no evidence of polarization variations with rotation
- no noticeable phase angle dependence

- **Pluto's surface is microscopically rough but not "asteroid-like"**
- **Polarization from a thin atmosphere adds to the surface polarization?**

NEW ERA IN POLARIMETRIC OBSERVATIONS

Plutino 28978 Ixion (2001 KX76)



Boehnhardt et al. 2004

R~ 19.7 mag

Telescope: 8 m VLT, FORS1

$P_{\min} \geq 1.3\%$

$\sigma_P \sim 0.1\%$

- unusually high negative polarization
- rapid changes with the phase angle

• **Two component surface model (mixture of bright and dark scatters)**

FIRST PROGRAM OF POLARIZATION MEASUREMENTS OF TNO AND CENTAURS

The polarimetric observations of Ixion demonstrated

(a) the capability of the instrument (FORS1 VLT) to provide good-quality observations of faint objects (~20 mag);

(b) the capability of the polarimetric technique to study distant objects even if they are observable only at very small phase angles.

The aim of new polarimetric observations was to probe surface properties of objects from different dynamical groups .

The following criteria were used to select objects :

- V≤ 21 mag. It lets to measure a polarization degree with accuracy better than 0.1% in less than two hours telescope time at 8 m telescope;
- the possibility to cover the largest phase angle range reachable from ground-based observations;
- dynamical group;
- availability of complementary information on object's physical properties.

LIST OF OBJECTS OBSERVED BY POLARIMETRIC TECHNIQUE

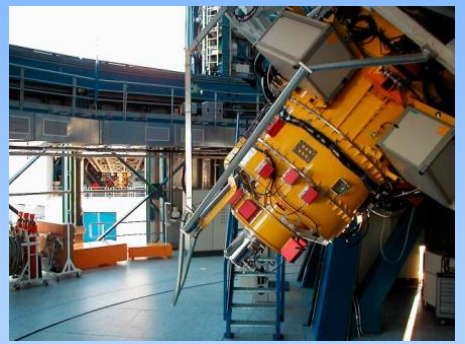
Object	Type	Group	α (deg)	Reference
(2060) Chiron	Centaur	BB	0.5–4.2	LP, Bagnulo et al. (2006)
(5145) Pholus	Centaur	RR-U	0.9- 2.6	LP, Belskaya et al. (2010)
(10199) Chariklo	Centaur	BR	2.7–4.4	LP, Belskaya et al. (2010)
(20000) Varuna	Classical	IR	0.1–1.3	LP, Bagnulo et al. (2008)
(26375) 1999 DE_9	Scattered	IR	0.1–1.4	LP, Bagnulo et al. (2008)
(28978) Ixion	Resonant	IR-RR	0.2–1.3	Boehnhardt et al. (2004)
(29981) 1999 TD_{10}	Scattered	BR	0.8–3.1	Rousselot et al. (2005)
(38628) Huya	Resonant	IR	0.6–2.0	LP, Bagnulo et al. (2008)
(50000) Quaoar	Classical	IR-RR	0.2–1.2	Bagnulo et al. (2006)
(134340) Pluto	Resonant	BR	0.7–1.8	Breger&Cochran (1982)
(136108) Haumea	Classical	BB	0.99	LP, Bagnulo et al. (2008)
(136199) Eris	Detashed	BB	0.1–0.6	LP, Belskaya et al. (2008)

Most part of the data were obtained as part of ESO-VLT Large Program (LP) in 2006-2008 (178.C-0036, PI: A. Barucci). POLARIMETRY TEAM:
I. Belskaya, S. Bagnulo, K. Muinonen, S. Fornasier, G.P. Tozzi, L. Kolokolova

POLARIMETRIC OBSERVATIONS WITH VLT

• 48 h of total observing time at VLT (service mode);

• observations with FORS1 using a remotely controlled rotatable half-wave retarder plate in front of the Wollaston prism;

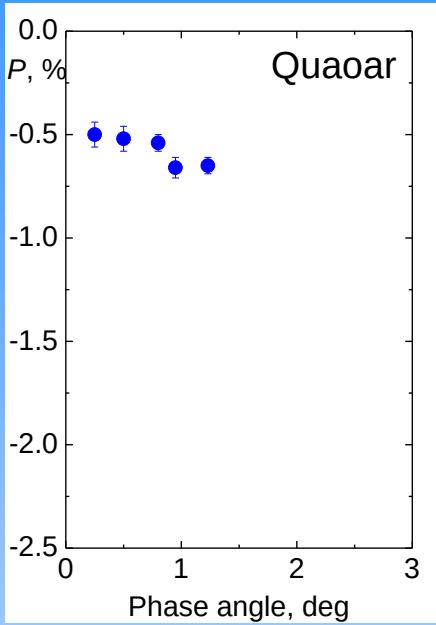


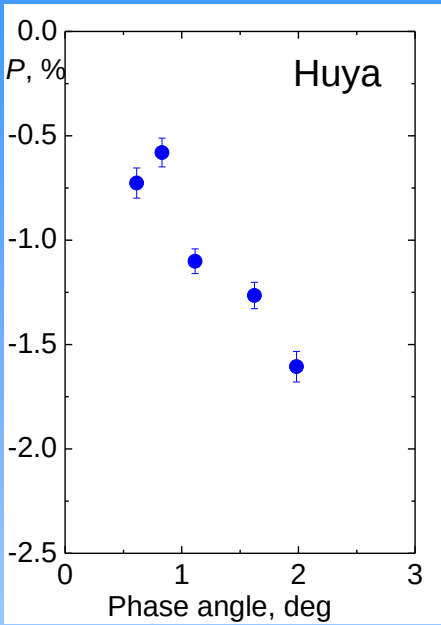
• measurements of the linear polarization in the Bessell *R* filter;

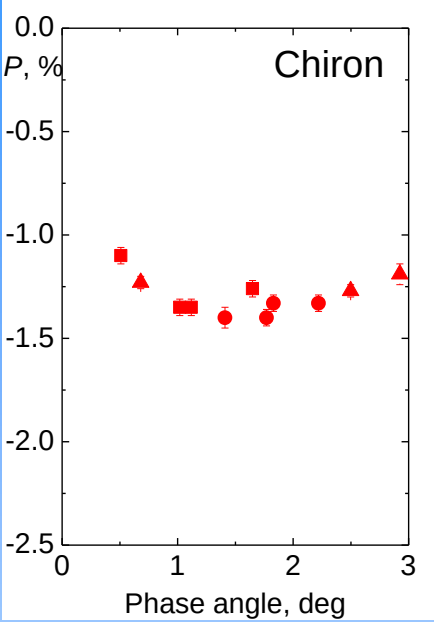
• instrumental polarization was well-controlled (an accuracy of 0.03% in *P* and 0.2° in the position angle *θ*).

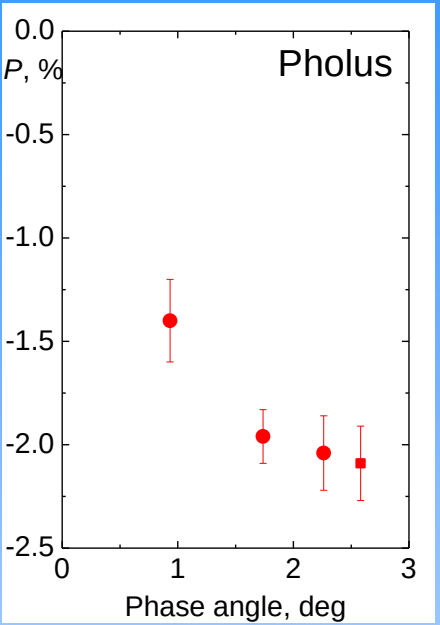
LP-VLT: 8 objects: 3 Centaurs, 2 classical, 2 resonant, 1 detached

DIVERSITY IN POLARIZATION PHASE BEHAVIOR







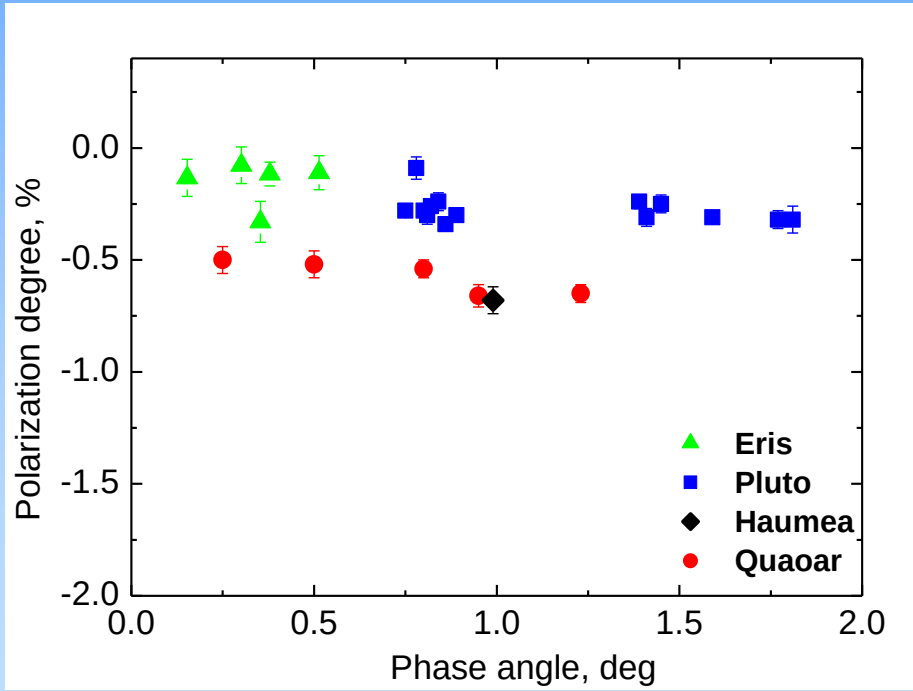


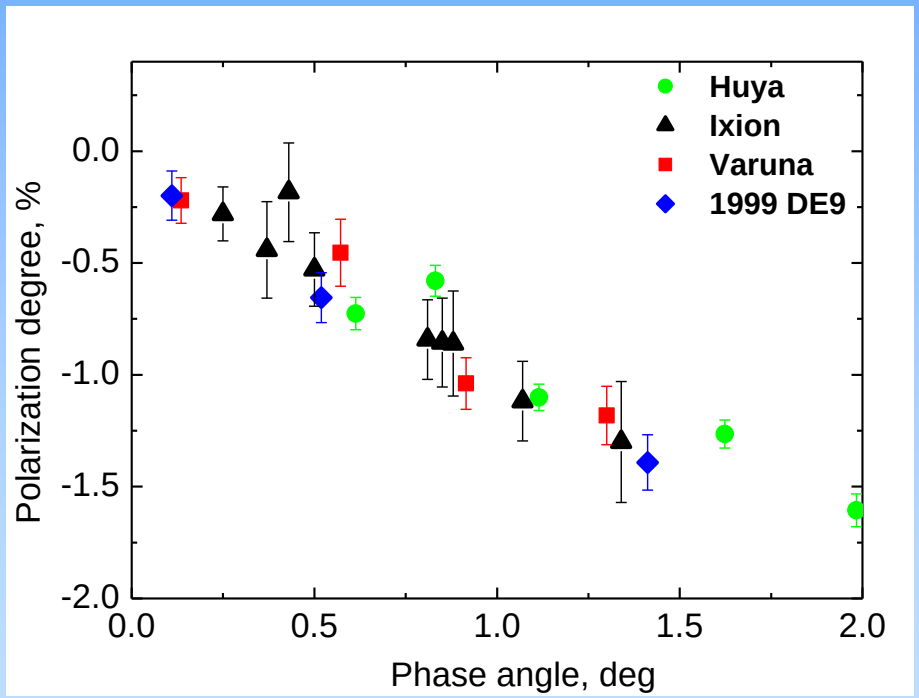
- **presence of the negative polarization, varying from -0.3% to -2.3%**
- **diverse phase angle behavior of polarization degree**

TWO BEHAVIOURS OF POLARIZATION-PHASE DEPENDENCES OF TNOs

- the largest objects (Eris, Pluto, Quaoar) show a shallow branch of the polarization-phase curve with slow changes of polarization with the phase angle;

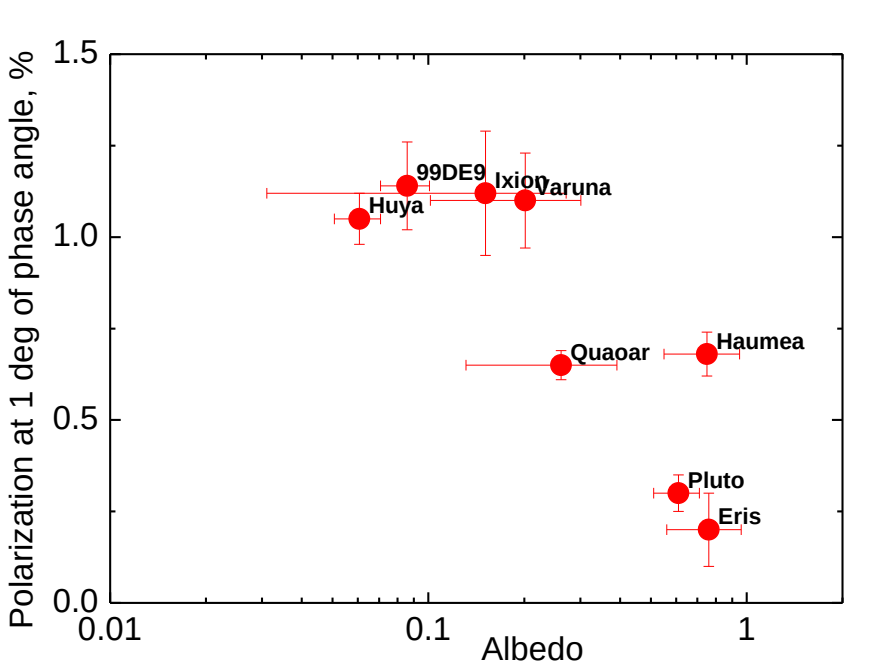
- the smaller objects (Huya, Ixion, Varuna, 1999 DE9) show a rapid enhancement in the negative polarization reaching about -1% at the phase angle of 1 deg.





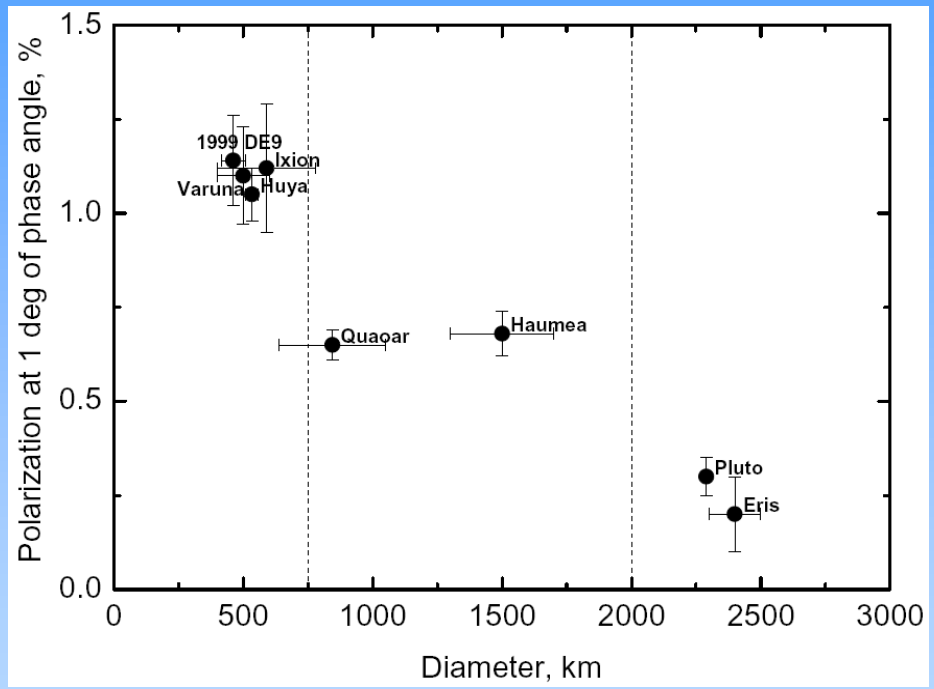
POSSIBLE REASONS OF TWO POLARIZATION BEHAVIOURS

Dependence of polarization degree on albedo?



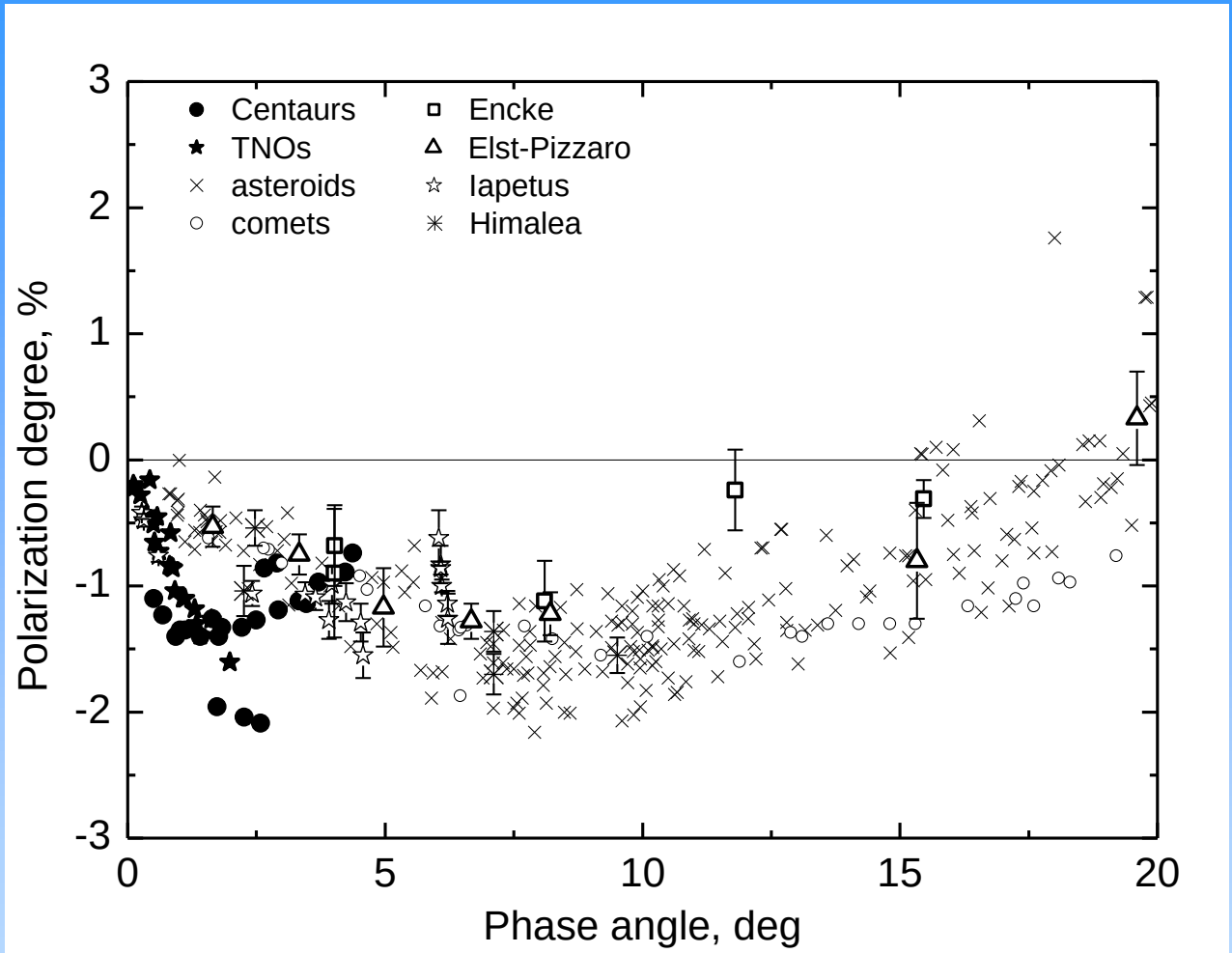
A single measurement of linear polarization of a TNO at the phase angle about 1 deg can provide a distinction between high- and low-albedo surfaces.

on capability of retaining volatiles?



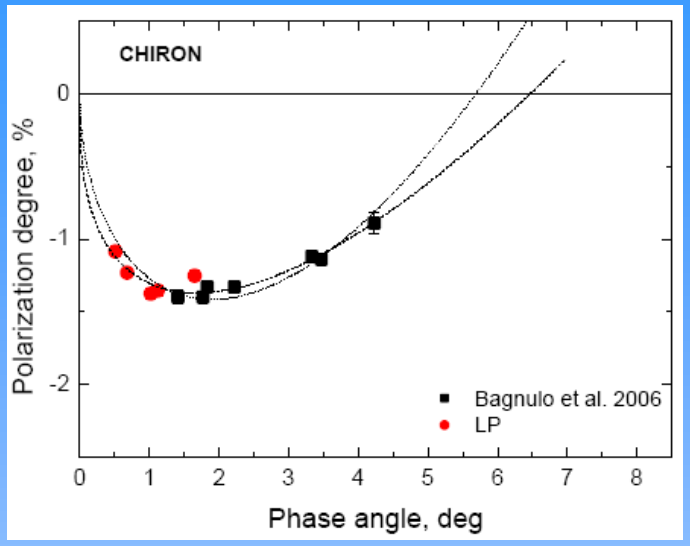
Vertical lines indicate the transition between volatile-free and volatile-rich surfaces according to Schaller&Brown (2007).

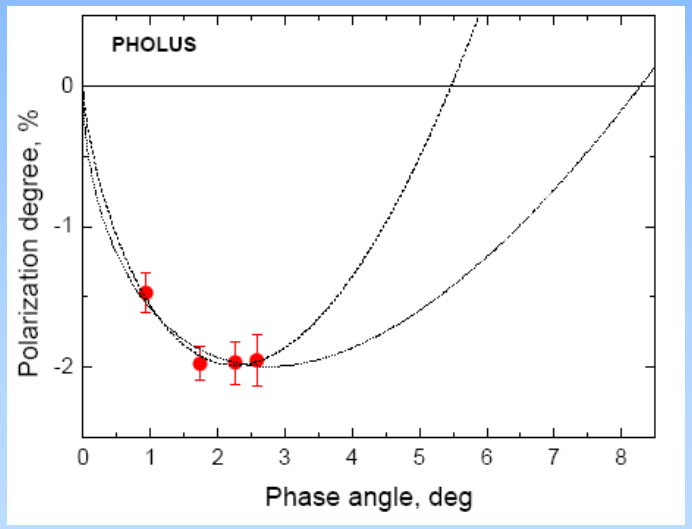
COMPARISON WITH OTHER SOLAR SYSTEM BODIES



Polarization phase behaviours of TNOs and Centaurs are significantly different from those measured for asteroids and satellites. Data are taken from ADS data-bases and Bagulo et al. (2008, 2010), Boehnhardt et al. (2008), Kiselev et al. (2010).

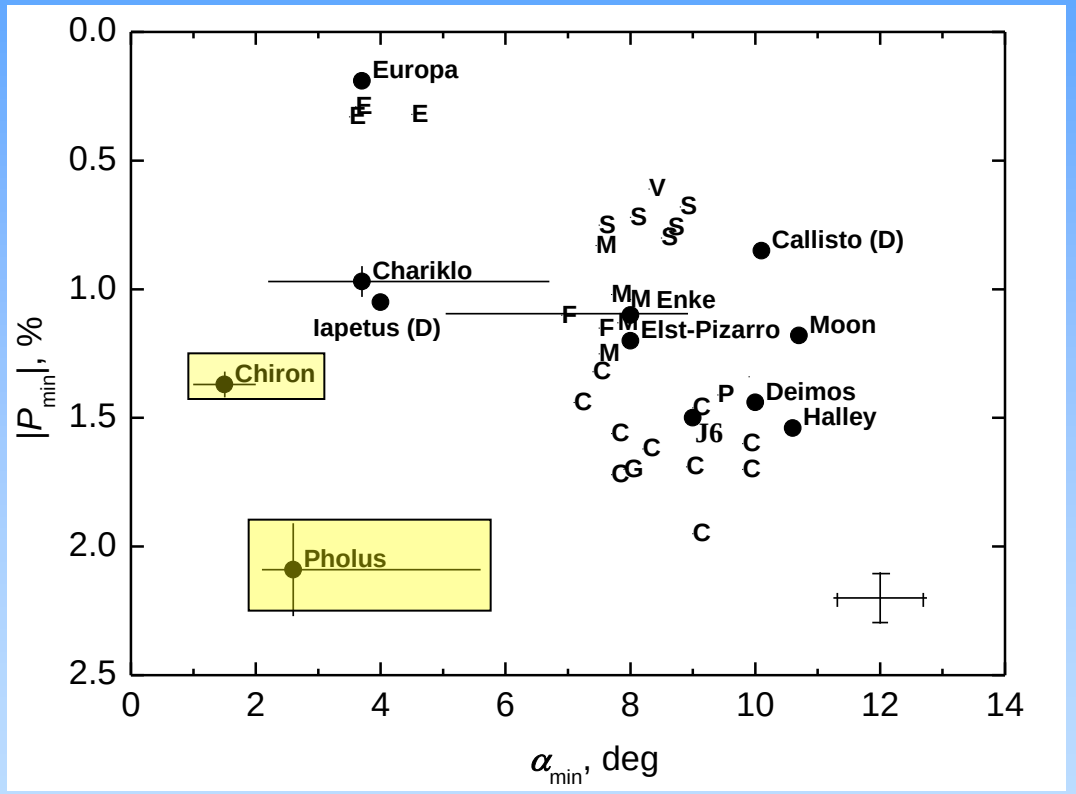
POLARIZATION MINIMUM





Chiron: α_{min}=1.6 deg, P_{min}=–1.4%;

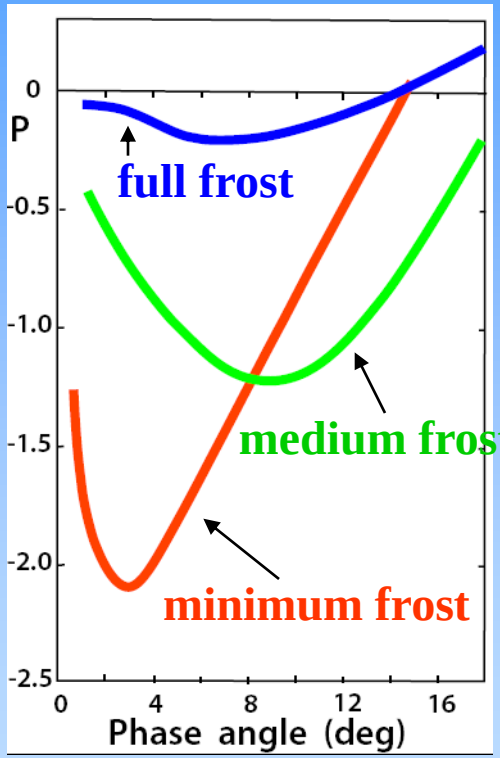
Pholus: $\alpha_{min}\geq$2.3 deg, P_{min}=–2.1%;



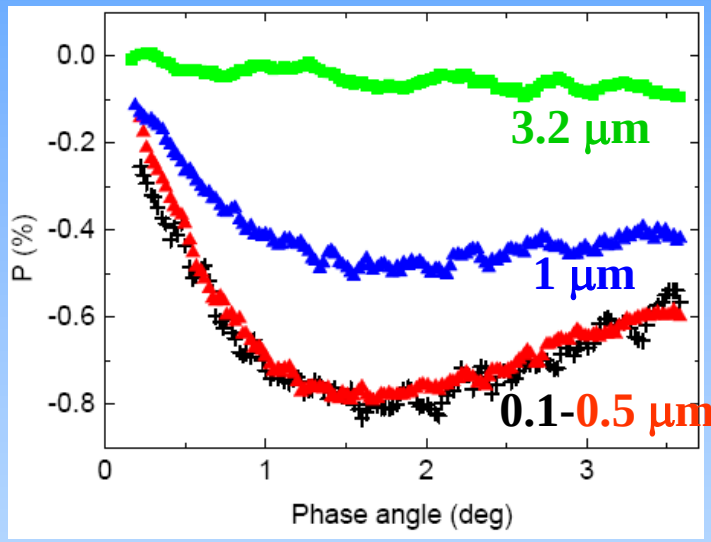
- Chiron shows the smallest phase angle of polarization minimum
- Pholus shows the deepest negative polarization branch at small phase angles

POSSIBLE REASONS OF SHIFT OF POLARIZATION MINIMUM TOWARD SMALL PHASE ANGLES

- fluffy surfaces with a large portion of submicron or micron-sized particles;
- inhomogeneous surface matter (scatterers with small and large single-scattering albedos).

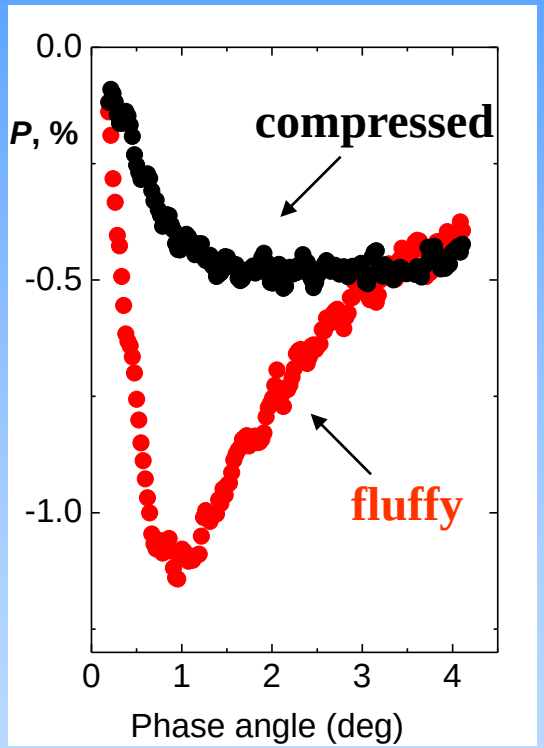


Frost of submicron ice crystals on a dark surface (Dougherty & Geake 1994)



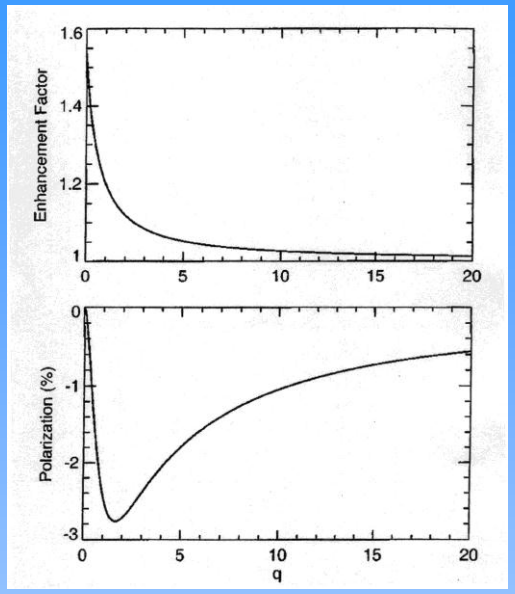
Sub-micron particles

Measurements of size-separated Al_2O_3 (Shkuratov et al. 2002)



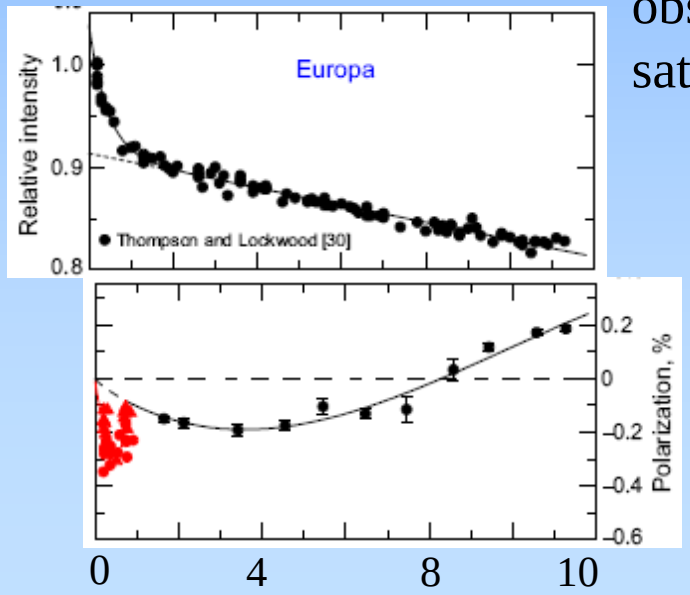
Fluffy and compressed MgO powder of ~1 μm (Shkuratov et al. 2002)

MODELING BASED ON THE COHERENT BACKSCATTERING MECHANISM

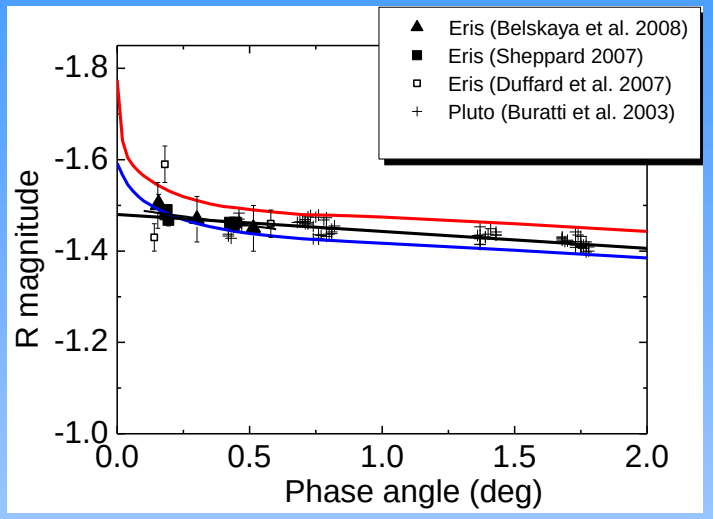


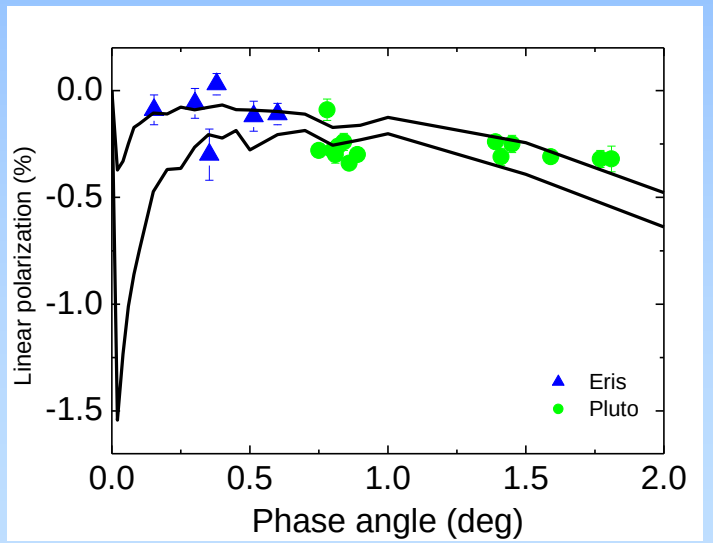
Mishchenko et al. (1993, 2006)

- effective for high albedo surfaces;
- brightness peak is accompanied by polarization peak of similar half-width;
- both effects were observed for bright satellites.



ERIS & PLUTO





Fit by Muinonen's model

CONCLUSIONS

• Polarimetric observations of 8 objects made within the ESO-VLT Large Program increase to 12 the number of TNOs and Centaurs for which polarimetric data are available. Noticeable negative polarization have been measured for all observed distant objects, varying from -0.3% to -2%. A dependence of polarization degree on object's albedo is well-seen.

• All four small TNOs (D<700 km) in our sample have similar polarization-phase dependences in spite of belonging to different dynamical groups. On the contrary, each of three Centaurs measured so far show different polarization-phase behaviour. It suggests a greater diversity of surface texture among Centaurs.

• Polarization phase behaviours both TNOs and Centaurs are significantly different from those measured for asteroids. It gives an evidence of different surface texture of these bodies.